

United States Marine Corps
Command and Staff College
Marine Corps University
2076 South Street
Marine Corps Combat Development Command
Quantico, VA 22134-5068

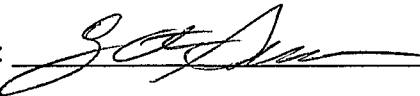
MASTER OF MILITARY STUDIES

NO WINGLETS: WHAT A DRAG...
ARGUMENT FOR ADDING WINGLETS TO LARGE AIR FORCE AIRCRAFT

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF MILITARY STUDIES


MAJOR JOEL W. SAFRANEK

AY 07-08

Mentor and Oral Defense Committee Member: 

Approved: ✓

Date: 11 March 2008

Oral Defense Committee Member: 

Approved: X

Date: 11 MARCH 2008

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE No Winglets: What a Drag...Argument for Adding Winglets to Large Air Force Aircraft				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) United States Marine Corps, Marine Corps Combat Development Command, Command and Staff College, Marine Corps University, 2076 South Street, Quantico, VA, 22134-5068				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 40	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Executive Summary

Title: No Winglets: What a Drag... Argument for Adding Winglets to Large Air Force Aircraft

Author: Major Joel W. Safranek, United States Air Force

Thesis: In order to save hundreds of millions of dollars in operating costs and improve aircraft capabilities, the Air Force should retrofit its existing large aircraft with winglets.

Discussion: The U.S. government faces a similar situation today that it did during the 1970's, growing instability in the Middle East contributing to the towering price of oil. As oil prices have escalated, so have political demands to decrease America's reliance on foreign oil; therefore, the U.S. government has begun placing a priority on ways to conserve energy. Building on ideas and concepts over a century old and Dr. Richard Whitcomb's, a NASA aeronautical engineer, research during the 1970's, retrofitting winglets to large aircraft has proven to decrease fuel consumption. Research with NASA and the U.S. Air Force proved retrofitting winglets on large aircraft decreased fuel consumption by 3 to 6 percent. Unfortunately for winglet technology, oil prices plummeted through the 1980's; and remained low through the 1990's, distracting the government's energy conservation priorities and burying the winglet concept for large military aircraft. The concept remained dormant for over two decades, until soaring energy prices have once again brought improving aircraft aerodynamic efficiencies to the forefront of the energy conservation debate. Displaying how winglets are a viable solution to decreasing fuel consumption with large Air Force aircraft, this paper attempts to tip the debate in favor of investing in retrofitting the Air Force's existing transport-type aircraft with winglets.

Conclusion: The data collected in this paper display the overwhelmingly positive arguments for retrofitting the Air Force's existing transport-type airframes with winglets.

DISCLAIMER

THE OPINIONS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE INDIVIDUAL STUDENT AUTHOR AND DO NOT NECESSARILY REPRESENT THE VIEWS OF EITHER THE MARINE CORPS COMMAND AND STAFF COLLEGE OR ANY OTHER GOVERNMENTAL AGENCY. REFERENCE TO THIS STUDY SHOULD INCLUDE THE FOREGOING STATEMENT.

QUOTATION FROM, ABSTRACTION FROM, OR REPRODUCTION OF ALL OR ANY PART OF THIS DOCUMENT IS PERMITTED PROVIDED PROPER ACKNOWLEDGMENT IS MADE.

Illustrations

	Page
Figure 1. Crude Oil Prices, 1970 – Aug 2007 (2006 Dollars).....	2
Figure 2A. Air Flow Pressure.....	4
Figure 2B. Vortex Wake from Induced Drag.....	4
Figure 2C. Conventional Wing vs. Blended Winglet.....	4
Figure 3. Total and U.S. Department of Defense Energy Consumption.....	6
Figure 4. U.S. Government Energy Consumption by Source.....	21
Figure 5. FY 05 Fuel Usage by U.S. Air Force Aircraft (Fleet).....	15
Figure 6. Boeing’s KC-135 Aircraft Winglet.....	18
Figure 7. Assessment of KC-135 Aircraft Estimated Net Savings.....	20
Attachment A. U.S. Government, DoD, and U.S. Air Force Fuel Utilization...	24
Attachment B. DoD Energy Consumption (FY05 Compared to FY06).....	25
Attachment C. Energy Consumption (DoD Compared to Rest of U.S.).....	26
Attachment D. DoD Mobility Use (FY03 — FY05).....	27
Attachment E. JP-8 (jet fuel) Costs, 1997 to 2007.....	28

Preface

As an Air Mobility Command (AMC) pilot, having flown both the KC-135 and C-17, I have witnessed a recent transformation in Air Mobility Command's attitude and priority toward fuel conservation—escalating fuel prices have not given the command much else of a choice. In recent years, AMC has taken low cost steps toward decreasing fuel consumption. AMC has increased centralized control over aircraft fuel loads, placed restrictions on aircraft fuel loads, removed parachutes and other unnecessary items (weight) from aircraft, and published flight crew information files educating pilots on the command's conservation concerns. Although all have had limited success, I believe you get what you pay for; and these actions have only scratched the surface of the command's real fuel savings potential. Unfortunately, taking real action toward decreasing fuel consumption requires massive upfront costs; and the command will most likely never do anything as significant as retrofitting aircraft with winglets without officers within the command pushing for such change; hence my reason for doing this research.

As with most things in life, you never get anywhere without the help of others. Therefore, I am grateful to Dr. Craig Swanson, Associate Dean of Academics, Marine Corps Command and Staff College, for his guidance as my thesis advisor during my research and writing. Most notably I must express my absolute appreciation for Ms. Marta Vornbrock, an Associate Program Officer for the Air Force Studies Board. Her emails were my treasure map, guiding me toward countless documents, presentations, websites, and the location of many other sources. Last, I am grateful to my wife for watching the kids and giving me the time and peace to work on the research in my "closet." I believe, even without their help, I would have been able to complete this research; but the road traveled would have been much more arduous. So I am sincerely indebted to each for making it an enjoyable journey instead of a painstaking process.

Table of Contents

	Page
DISCLAIMER.....	ii
LIST OF ILLUSTRATIONS.....	iii
PREFACE.....	iv
FAILING TO STUDY HISTORY.....	1
WHAT WINGLETS ARE AND HOW THEY WORK.....	3
WINGLETS AS A NATIONAL SECURITY PRIORITY.....	6
NATIONAL POLICY STUDIES AND DIRECTIVES.....	11
A WINGLET CASE STUDY: THE KC-135 STRATOTANKER.....	15
CONCLUSION AND RECOMMENDATIONS.....	22

Failing to Study History

The recent escalation of fuel costs and the threat of future increases have quickly brought to the forefront the need to improve aircraft efficiency.

— *Design and Analysis of Winglets for Military Aircraft, 1976*¹

They say those who cannot remember the past are condemned to repeat it, and that has definitely been the case with the military's failing to improve aircraft efficiency in order to decrease fuel consumption.² During the 1970's, growing instability in the Middle East (e.g. the oil embargo due to U.S. support for Israel, the Iranian Revolution, and the Iran/Iraq War) contributed to the price of oil sky rocketing over 250 percent within three years. Between 1978 and 1981, oil prices soared from an average price per barrel of \$14.35 to \$36.47.³ As the price of oil escalated, so did political demands to decrease America's reliance on foreign oil. With the entire world focused on high oil prices, the U.S. government began placing a priority on ways to conserve energy. Building on ideas and concepts over a century old, Dr. Richard Whitcomb, an aeronautical engineer at the National Aeronautics and Space Administration (NASA), rekindled the idea of adding winglets to aircraft wings. Research with NASA and the U.S. Air Force proved retrofitting winglets on large aircraft decreased fuel consumption by 3 to 6 percent. Unfortunately for winglet technology, oil prices plummeted through the 1980's; and remained low through the 1990's, distracting the government's energy conservation priorities and burying the winglet concept for large military aircraft. The concept remained dormant for over two decades, until soaring energy prices have once again brought improving aircraft aerodynamic efficiencies to the forefront of the energy conservation debate. Displaying how winglets are a viable solution to decreasing fuel consumption with large Air Force aircraft, this paper hopes to tip the debate in favor of investing in retrofitting the Air Force's existing transport-type aircraft with winglets.

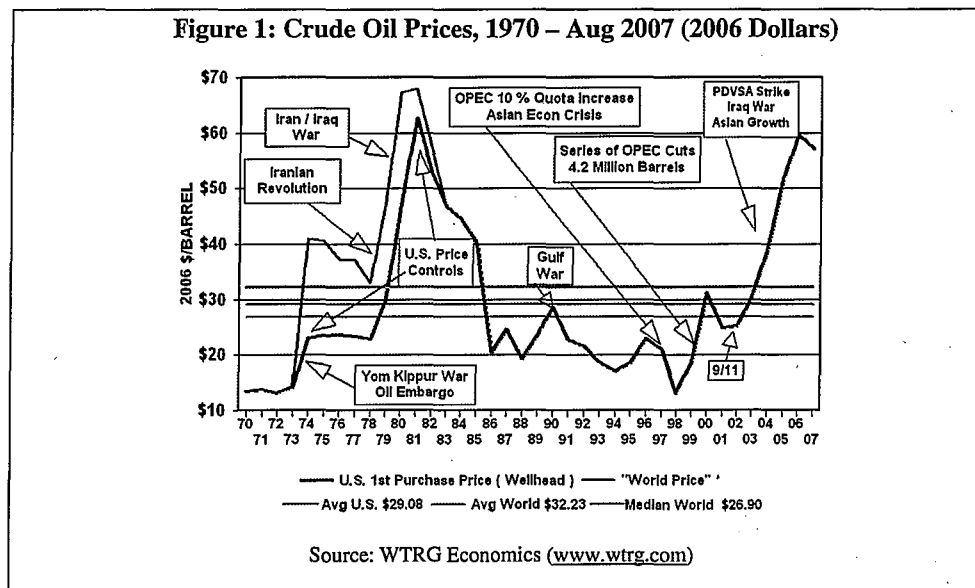
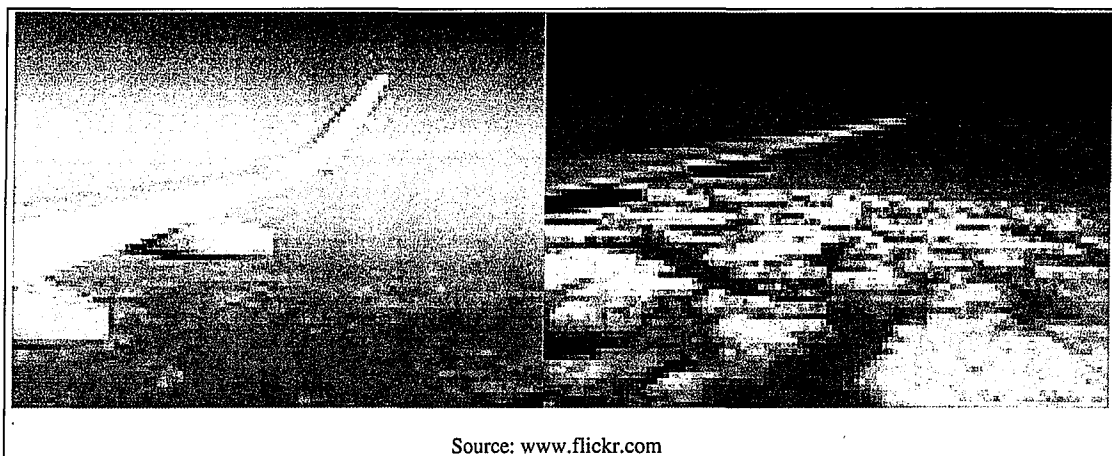


Figure 1 displays how the situation with recent crude oil prices is very similar to that of the late 1970's. Additionally, with recent trouble in the Middle East adding to the towering oil prices, politicians are once again calling for the government to focus attention on energy conservation and the need to decrease America's reliance on foreign oil and other fossil fuels. With oil prices once again at historical highs, the Air Force, once again, faces the decision of whether or not to retrofit its large transport-type aircraft with winglets. In order to address the same problem in the commercial world and maintain bottom lines in the black, recent years have witnessed major airlines retrofitting their older aircraft with winglets. Failing to follow the lead of major airlines, who have grasped winglets as an investment in decreasing operating costs and improving capabilities, the Air Force has yet to retrofit its tanker and transport aircraft. This failure continues costing America hundreds of millions of dollars, comparatively limits mobility capabilities, and continues to feed the government's insatiable thirst for energy. Unless the government learns from past mistakes, it will once again pass on retrofitting aircraft with winglets; and miss an opportunity to decrease the government's dependence on foreign oil, save millions in operating costs, and increase aircraft capability.

What Winglets Are and How They Work

Simply put, more miles will be traveled, both by combat units and the supply units that sustain them, which will result in increased energy consumption. Therefore, DoD must apply new energy technologies that address alternative supply sources and efficient consumption across all aspects of military operations.

— Transforming the Way DOD Looks at Energy, 2007⁴



Source: www.flickr.com

Ask most people to tell you the difference between the two aircraft wings shown, and most will reply on the physical characteristics: one has a vertical extension; the other does not. Almost all will miss the most significant difference: the one on the left saves hundreds of millions of dollars; the one on the right does not. The vertical extension in the picture on the left is called a winglet. Winglets are small, nearly vertical aerodynamic surfaces mounted on aircraft wingtips. Engineers design them with the same careful attention to airfoil shape and local flow conditions as the wing itself. The primary benefit of adding a winglet is decreased fuel consumption. Additionally, winglets provide many positive side effects: increased aircraft range, greater payload, improved take off performance and decreased engine wear.⁵ All of which correlate to increased capability and decreased operating costs. Although a 3 to 6 percent savings may not seem like a lot, it equates to a tremendous amount of fuel when you consider larger aircraft which burn between 1,500 and 2,200 gallons an hour. The Air Force has hundreds of such large aircraft. A large majority are without winglets, costing taxpayers hundreds of

millions of dollars—not to mention the environmental issue of needlessly wasting millions of gallons of fuel each year.

Understanding basic aerodynamics leads to a fuller understanding of a winglet's potential. In very basic terms, four factors affect all aircraft: 1) lift, 2) thrust, 3) weight, and 4) drag. While lift and thrust are positive factors, helping an aircraft fly, weight and drag are negative factors, working against an aircraft's ability to fly. Two sources of drag affect aircraft performance, parasitic and induced drag. Parasitic drag is drag caused by moving a solid object through a fluid. Induced drag is drag created as a consequence of producing lift by a wing. In order to create lift and allow an aircraft to fly, an aircraft's wing is shaped to generate negative pressure on the upper surface and positive pressure on the lower surface of a wing. However, the unequal pressure also causes air to flow outward along the lower surface of the wing. As the air flow encounters the tip of a wing, it rolls up over the edge (see Figure 2A). As the opposing air flows meet, they create a whirlwind motion called vortices (see Figure 2B). The transfer of energy expended from the wing to the air in this phenomenon is directly responsible for induced drag.

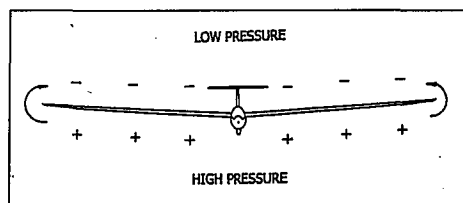


Figure 2A: Air Flow Pressure
Source: "About Winglets" by Mark Maughmer

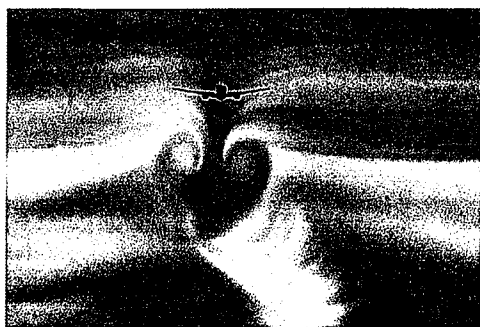


Figure 2B: Vortex Wake from Induced Drag
Source: Airlines.net

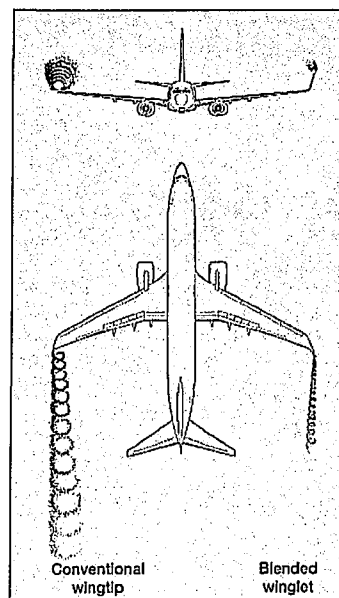


Figure 2C: Conventional Wing vs. Blended Winglet
Source: Aviation Partners Boeing

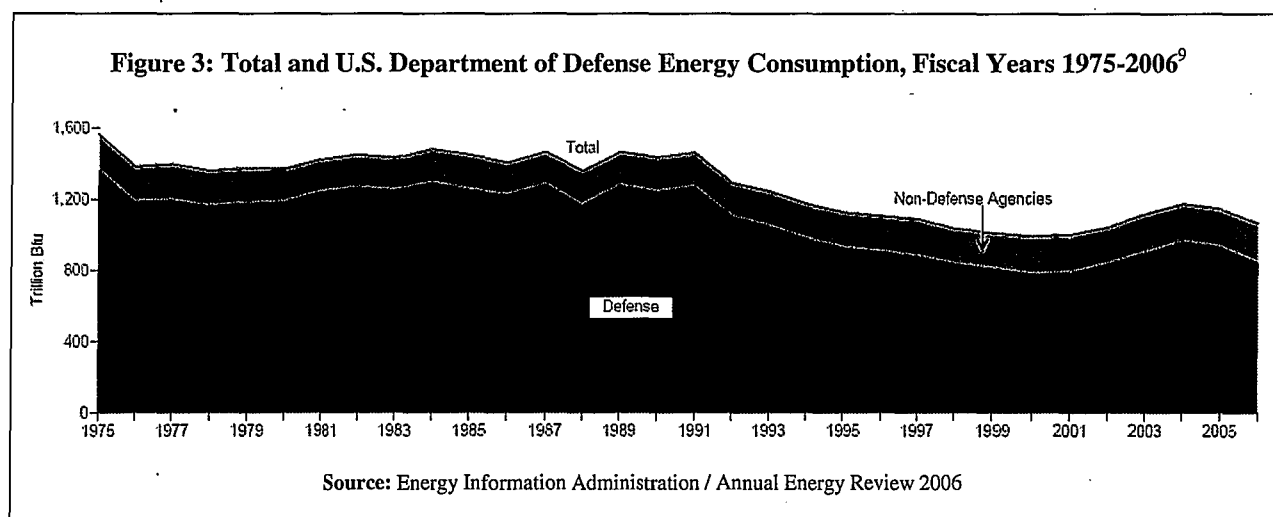
Induced drag can be extremely large for certain aircraft wing configurations, particularly those found on large transport-type aircraft. More specifically, Dr. Whitcomb discovered induced drag significantly diminishes aircraft efficiency for transport-type aircraft operating at high subsonic speeds (e.g. cruise conditions), accounting for as much as 50 percent of the total drag.⁶ Since winglets, designed as small airfoils, reduce the aerodynamic drag associated with vortices by minimizing the amount of energy used in producing the required downwash, winglets specifically diminish induced drag (see Figure 2C). Therefore, a winglet, with its main purpose of reducing induced drag, is the perfect solution for aircraft affected greatly by induced drag, such as those of large transport-type aircraft.

Winglets as a National Security Priority

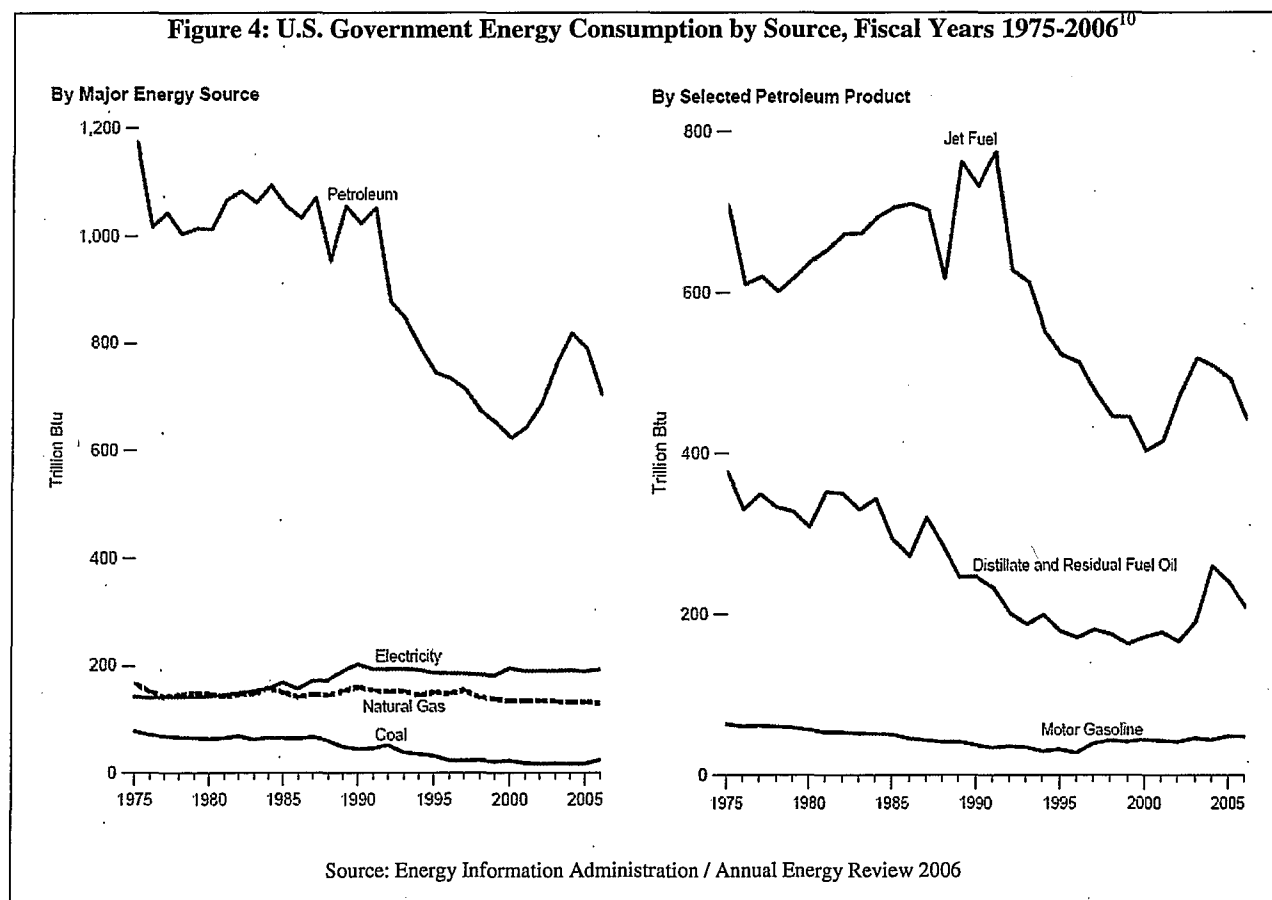
At present, the United States imports roughly 63 percent of its crude oil from foreign sources, and its rate of consumption of fossil fuels is increasing by approximately 1.5 percent per year, while its production capability has slightly decreased in the last decade. Increasing oil demand by highly populous nations such as India and China, at rates nearly four times that of the United States, will increase (and are increasing) the potential for geopolitical tension regarding fossil fuels. Hence fuel availability, as well as more efficient utilization of fuel, will be increasingly critical issues for the foreseeable future.

— USAF Scientific Advisory Board, 2006⁷

Although the previous section explains the science behind winglets, it leaves most wondering how decreasing drag 3 to 6 percent can really be that significant. When considering the data, the numbers are staggering. The U.S. government is the largest single user of energy within the United States (and most likely the world), representing approximately 2 percent of the nation's entire energy usage. Within the federal government, the Department of Defense (DoD) is easily the most dominant player in energy consumption, accounting for more than 90 percent of the government's overall energy budget (approximately 1.8 percent of the nation's energy usage).⁸ Regardless of a 25 percent reduction in DoD energy use over the past three decades, Figure 3 displays how the DoD continues to be the government's energy juggernaut. Therefore, it is easy to see how the smallest percentage of decrease in DoD energy demands easily has a significant impact across the entire federal government.



When analyzing the federal government's energy consumption, one dominant fact surfaces, petroleum is the key to decreasing federal government energy demands; and when analyzing petroleum consumption, one dominant fact surfaces, jet fuel is the key to decreasing petroleum demands. Examining the fuel sources the government uses most reveals petroleum usage vastly exceeds all other sources of energy combined. Figure 4 displays how petroleum use has declined significantly over the past three decades, but still accounts for approximately two-thirds of all energy consumed by the federal government. Additionally, Figure 4 displays when breaking down petroleum specific products, jet fuel is the dominant product, accounting for just under two-thirds of all petroleum and almost half of all energy consumed by the federal government. Therefore, petroleum and more specifically jet fuel must be included in any attempt to reduce the federal government's energy demands.



With the federal government's petroleum usage representing more than 1 percent of the entire nation's total energy use and the DoD's dominating petroleum use within the federal government, it is vastly important to analyze how the DoD's petroleum use breaks down. In the case of breaking it down by individual service, the U.S. Air Force is by far the largest user of energy and specifically petroleum within the DoD, representing approximately 57 percent of all DoD petroleum use (see Attachment A).¹¹ In the case of breaking it down by petroleum source, jet fuel is by far the largest source of petroleum consumed within the DoD. For example, in FY 2005 and FY 2006, jet fuel usage accounted for over half of the energy DoD consumed (see Attachment B). By comparison, the remainder of the nation (not including the DoD) only relied on jet fuel for 4 percent of its energy needs; and as expected, the Air Force is the largest consumer of jet fuel within the DoD (see Attachment C). In the case of specific military missions, the DoD allocates a predominant amount of its energy resources to its mobility mission which accounts for 94 percent of the DoD's petroleum consumption and approximately 75 percent of all DoD energy use (see Attachment D).¹² Once again, the Air Force represents the lion's share of mobility petroleum use, consuming approximately 57 percent of DoD's mobility fuel (see Attachment D). Therefore, the U.S. Air Force, and more specifically its mobility mission, are at the crossroad for any real demand decrease in DoD (and federal government) petroleum use.

When examining DoD and Air Force energy consumption, the apparent reliance on jet fuel is astronomical. U.S. military doctrine relies heavily on air power as an integral part of the joint force, and air power relies heavily on jet fuel. Therefore, the agility, mobility, and speed which air power provides come at a high cost and a further reliance on liquid petroleum. For example, the Air Force spends over 80 percent of its \$6.7 billion energy budget (approximately

\$5 billion) purchasing more than 3 billion gallons of aviation fuel each year (over 8 million gallons per day).¹³ Within the Air Force, mobility aircraft consume the largest share of jet fuel (approximately 54 percent), placing the largest fuel budget burden on the Air Force's Air Mobility Command (AMC).¹⁴ AMC consumed \$1.3 billion worth of jet fuel in fiscal year (FY) 2005 and \$1.8 billion for FY 2006. Expenditures for FY 2007 put AMC on pace to surpass \$2 billion.¹⁵ With AMC's consuming such quantities of aviation fuel, the federal government (and the Air Force) can no longer ignore the alarming rise in jet fuel prices. Within recent years, the federal government has had to deal with annual aviation fuel price increases of up to 47.9 percent (see Attachment E).¹⁶ For example, JP-8, the DoD's primary jet fuel, increased from \$0.91 per gallon in FY 2004 to \$2.58 per gallon in FY 2006 (a factor of over 2.8 in just two years).¹⁷

The government estimates every \$10 increase per barrel of oil costs the DoD an additional \$1.5 billion, and specifically the Air Force an additional \$600 million; therefore, recent years' rapidly rising fuel prices have had a devastating effect on government fuel budgets.¹⁸ For example, the Air Force exceeded its aviation fuel budgets by \$1.4 billion and \$1.6 billion in FY 2005 and 2006, respectively.¹⁹ Since the DoD budgets for fuel a year or more in advance of its purchase, such sudden increases in fuel costs must be paid for with emergency funds or by shifting funds from other programs.²⁰ In an attempt to combat this, the Air Force tagged an additional \$1.1 billion within its FY 2007 budget specifically to cover expected an expected 36 percent increase in fuel rates—it was not enough.²¹ If this past year's \$40 spike in oil remains, future increases could require the Air Force's funding an additional \$2.4 billion—close to \$1 billion alone for mobility platforms.

Given that approximately 30 percent of the DoD's petroleum use is related specifically to mobility aircraft, it represents the greatest potential energy savings; and with the increasing and

compelling rationale for reducing fossil fuel use, the government must invest in vehicle technology options such as winglets to enable fuel-use reductions. While winglets may not serve as a single silver bullet, reducing the DoD dependence on fossil fuels, it is one of many steps, in aggregate which the government should undertake. As with sailing racing, one can win (and win big) by not losing in lots of little ways; and that is how the 3 to 6 percent savings winglets offer become a significant factor in decreasing DoD (and national) fuel consumption. With AMC's being the single largest user of aviation fuel within the federal government, targeting aerodynamic efficiency improvements in large mobility aircraft is not only an AMC or Air Force priority, but a national priority.

National Policy Studies and Directives

“The two biggest challenges that I would like to see solved in the next two and half years. One...the unfunded liabilities inherent in social security and medical care.... And the other is energy. ...It’s not just an economical security issue, it’s a national security issue.”

— President George W. Bush, 30 August 2006

As crude oil prices and worldwide competition for fuel have continued to increase within recent years, the U.S. government has followed a path similar to that of the 1970’s, increasing its research on fuel reduction within the military. Although the research has led the DoD to understand there is no one silver bullet, conclusions have continually highlighted increasing aircraft aerodynamic efficiency through technology and the benefits of adding aircraft winglets. In 2001, the Defense Science Board conducted the earliest comprehensive DoD study on fuel use; and focused on weapon system fuel efficiency. The board made five findings: 1) the DoD requirements and acquisition process does not value the cost benefits of fuel-efficient weapons systems, 2) DoD decision making does not reflect true fuel costs, masks energy efficiency benefits, and distorts platform design choices, 3) the DoD resource and accounting processes do not reward fuel efficiency or penalize inefficiency, 4) wargaming involving fuel requirements are not cross-linked to service requirements, development or acquisitions, and 5) high payoff, fuel-efficient technologies are available to current weapon systems via retrofitting.²² Simply put, the DoD has no idea how much fuel really costs in the battlefield; and continues to waste and drain this valuable resource in mass because it refuses to place fuel efficiency on the same playing field as other operational requirements in the weapon system acquisition decision-making process.

With no end in sight for fuel price increases, 2006 kicked off a frenzy of government reports on energy conservation. In May 2006, the Air Force Scientific Board released its report, *Technology Options for Improved Air Vehicle Fuel Efficiency*, which recommended, “In the near

term, wing retrofits such as winglets have demonstrated the potential for increased L/D [lift over drag] per aircraft, and hence improved fuel efficiency, with a relatively modest potential cost."²³ The federal government followed in September 2006 with two additional comprehensive studies. The JASON report, *Reducing DOD Fossil Fuel Dependence*, emphasized the value of optimizing weapon system energy efficiency over pursuing alternative fuels.²⁴ The Defense Task Force on Energy Security, an internal cross-functional group led by the Director of Defense Research and Engineering, also backed the concepts of increasing weapon system energy efficiency and incorporating the energy efficiency component into the acquisition process.²⁵

More recently, LMI Government Consulting, Inc. completed a government sponsored report, *Transforming the Way DoD Looks at Energy*, in April 2007; and recommended incorporating energy considerations into the DoD's key corporate decision making (i.e. acquisition; and planning, programming, budgeting and execution). The report specifically cited Boeing's wing-tip program as an example for changing aerodynamic design in order to improve fuel efficiencies.²⁶ Additionally, a Congressional Research Service study, *The Department of Defense: Reducing Its Reliance on Fossil-Based Aviation Fuel – Issues for Congress*, reported to Congress in June 2007, citing winglet technologies as a viable option for decreasing DoD fuel demand.²⁷ The study gave options for Congress to mandate fuel efficiencies in aircraft and mandate fuel efficiencies as a consideration in new DoD acquisitions.²⁸ A consistent theme in all the government reports indicates the DoD needs to consider technology advancements as a way of reducing demand for fossil fuel. In particular, they highlight the reduction of aviation fuel as a primary target due to its accounting for the largest share of DoD fuel consumption.

The government has seen the reports, heard the briefings, and has begun to mandate decreases in energy demand. On 24 January 2007, President Bush signed Executive Order

13423, *Strengthening Federal Environmental, Energy, and Transportation Management*, which contained language modifying the annual energy reduction specified by Public Law 109-58 to 3 percent per year or 30 percent by 2015.²⁹ Understanding the significance of targeting aviation fuel for reduction and the need to improve weapon system energy efficiency, Congress has also taken action, placing language in the FY 2007 Defense Authorization and Appropriations Acts. The language required the DoD to report to Congress on their actions to reduce consumption of fossil fuel and increase the energy efficiency of their weapon platforms.³⁰ More specifically, the House Committee on Armed Services, in its report (House Report 109-452, 5 May 06) on House Report 5122 specifically addressed the issue of adding winglets to military aircraft, stating,

The committee commends the Air Force in its efforts to increase aircraft fuel efficiency and decrease fuel consumption. The committee notes that initiatives such as re-engining aircraft, modifying in-flight profiles, and revising aircraft ground operations contribute to decreased fuel consumption and increased life-cycle savings. The committee is aware that winglet technology exists for aircraft to increase fuel efficiency, improve take-off performance, increase cruise altitudes, and increase payload and range capability. The committee notes that winglets are currently used on commercial aircraft and result in a five to seven percent increase in fuel efficiency. On September 16, 1981, the National Aeronautics and Space Administration released the *KC-135 Winglet Program Review* on the incorporation of winglets for KC-135 aerial refueling aircraft. However, the Air Force concluded that the cost of adding winglets to the KC-135 did not provide sufficient payback in fuel savings or increased range to justify modification. Although the Air Force did conclude that modifying aircraft with winglets could increase fuel efficiency, the Air Force determined that re-engining the KC-135 aircraft produced a greater return on investment. The committee believes that incorporating winglets on military aircraft could increase fuel efficiency on certain platforms and that the Air Force should reexamine incorporating this technology onto its platforms. Therefore, the committee directs the Secretary of the Air Force to provide a report to the congressional defense committees by March 1, 2007, examining the feasibility of modifying Air Force aircraft with winglets.³¹

The Air Force has responded to the President and Congress. On 27 February 2007, Mr. Michael Aimone, Air Force Assistant Deputy Chief of Staff/Logistics, Installations and Mission Support, testified before the Senate on the Air Force's three-fold energy strategy to include "implementing aggressive demand side fuel optimization and energy efficiency initiatives laser-focused on each of our three energy sectors [one being aviation operations]."³² In conjunction with the National Research Committee, the Air Force Studies Board also released *Assessment of Wingtip Modifications to Increase the Fuel Efficiency of Air Force Aircraft*, addressing the

research and potential benefits of winglet technology.³³ Therefore, the stage has been set, the federal government has required demand reductions, the Air Force has promised demand reductions, and the technology exists to make it happen, forcing future actions to decrease jet fuel demand.

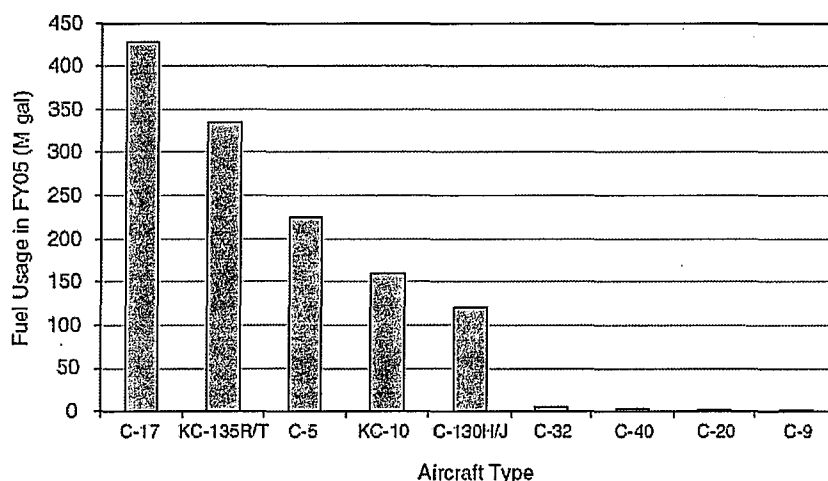
A Winglet Case Study: The KC-135 Stratotanker

The Air Force is the largest DoD consumer, and spends approximately 85 percent of its fuel delivery budget to deliver, by airborne tankers, just 6 percent of its annual jet fuel usage.

— *More Capable Warfighting Through Reduced Fuel Burden, 2001*³⁴

Due to its unique mission the KC-135 is a perfect example for how improving its fuel efficiency can have tremendously amplified benefits. As previously stated, mobility aircraft consume the largest share of mobility fuel within the DoD and the largest share of jet fuel within the Air Force. When comparing aircraft without winglets, the KC-135 fleet is the largest consumer of fuel within the Air Force's mobility fleet, using more fuel than the KC-10 and C-130 fleets combined (see Figure 5). Additionally, the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics released a report, *More Capable Warfighting Through Reduced Fuel Burden*, in 2001 which discovered the DoD priced fuel based on wholesale refinery prices and did not include the delivery cost. Therefore, the DoD's accounting process is flawed and does not reflect the true cost of fuel. For example, in FY 2001, the Defense Energy Supply Center's fuel mix price (average price of fuels sold) was \$1.337 per

Figure 5: FY05 Fuel Usage by U.S. Air Force Aircraft (Fleet)³⁵



NOTE: The C-17 has always had winglets.

Source: Defense Energy Supply Center

gallon, but the costs associated with delivering fuel via air refueling with a KC-135 brought that same cost to \$17.50 per gallon.³⁶ Match \$17.50 a gallon with aircraft capable of burning 1,500 to 2,200 gallons an hour; and it is easy to see how small improvements in the KC-135's fuel efficiency can have further reaching second and third level effects on fuel budgets.

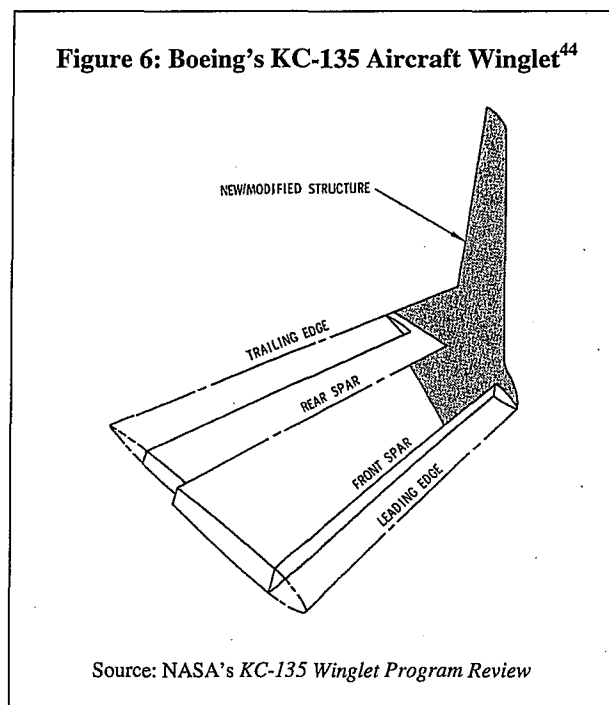
History shows the government understood the far reaching benefits of improving the KC-135's aerodynamic efficiency thirty-five years ago. With the advent of the 1973 fuel crisis, the fuel efficiency of transport-type aircraft became paramount to the federal government. In order to improve the fuel efficiency of such aircraft, the government became particularly interested in Dr. Whitcomb's development of wingtip mounted winglets which reduced the drag of the wing lifting system. After witnessing his theories in motion with McDonnell Douglas's wind tunnel testing of a DC-10 with winglets showing a 5 percent drag reduction and Boeing's engineering study of a 747 with winglets predicting a 4 percent drag reduction, the government targeted its two largest fuel consumers, the KC-135 and C-141 aircraft.³⁷ The government initiated a number of studies over the following years to determine the suitability of adding winglets to both aircraft.

The Air Force, in a joint project with NASA, furthered Dr. Whitcomb's research in the design and fabrication of winglets for the KC-135 aircraft, examining the feasibility of winglets on KC-135 aircraft and the effect of winglets on vehicle aerodynamic characteristics. In February 1976, the Air Force published *Design and Analysis of Winglets for Military Aircraft*. With the document providing analytical data estimating winglets would significantly decrease drag and improve range, the government concluded installing winglets on the KC-135 was worth further investigation. NASA and the Langley Research Center then proceeded to test the computer models with extensive wind tunnel tests. Throughout 1976, NASA and Langley tested

a semi-span KC-135 model with winglets in an eight-foot transonic tunnel which resulted in indications of an 8 percent total drag reduction at cruise flight conditions. The successful tests, subsequently, led to testing a full span KC-135 model with winglets in the transonic tunnel, indicating drag reductions of 6 percent at cruise. With analytical studies confirming wind tunnel tests, researchers concluded drag decreases of 6 to 8 percent.

By 1977, the price of oil had become almost unbearable and conditions in the Middle East did not appear to be improving. Additionally, NASA released *Theoretical Parametric Study of the Relative Advantages of Winglets and Wing-tip Extensions* in September of 1977 which made two definitive statements. First, after reviewing a wide range of wings, NASA concluded winglets had a greater gain in induced efficiency than wing tip extensions. Second, the document stated, "[recent experiments] demonstrate that winglets could significantly improve the efficiency of transport aircraft," specifically highlighting transport-type aircraft over other types due to their specific wing designs.³⁸ With successful analytical and wind-tunnel testing, increasing oil prices, and research highlighting transport-type aircraft, the Air Force contracted Boeing to conduct a feasibility study and an advanced development program to build and flight test a set of winglets on a KC-135.³⁹ Boeing determined no basic aerodynamic, structural, or dynamic problems existed with KC-135 winglets. The investigation also concluded the reduction in drag translated to a fuel savings of 44 million gallons per year for the KC-135 fleet, correlating to a cost savings of \$17.5 million a year (1977 dollars). Additionally, Boeing calculated a fleet-wide retrofit cost of about \$42.5 million, placing the government's break even point at less than three years.⁴⁰

By the end of 1977, Boeing had the contract to design, fabricate, and ground test a set of winglets, and modify the outer wing panels to accept winglets. It completed design reviews in 1978; and in 1979, constructed and began flight testing of the first winglet.⁴¹ Flight tests proved the addition of winglets improved aircraft efficiencies, reducing total aircraft drag for all Mach speeds and lift coefficients tested.⁴² The most significant results came in the cruise performance tests, revealing improvements in fuel mileage associated with the installation of winglets on the KC-135.⁴³ Although the flight tests measured fuel mileage improvements between 3.1 percent and 5.5 percent, corrections to the



flight measured data for surface pressure differences between wind tunnel and flight tests resulted in fuel mileage improvements between 4.4 percent and 7.2 percent.⁴⁵ Considering all the data and optimum cruise conditions, researchers concluded the data showed a KC-135 winglet retrofit program would provide a 6 percent performance improvement.⁴⁶

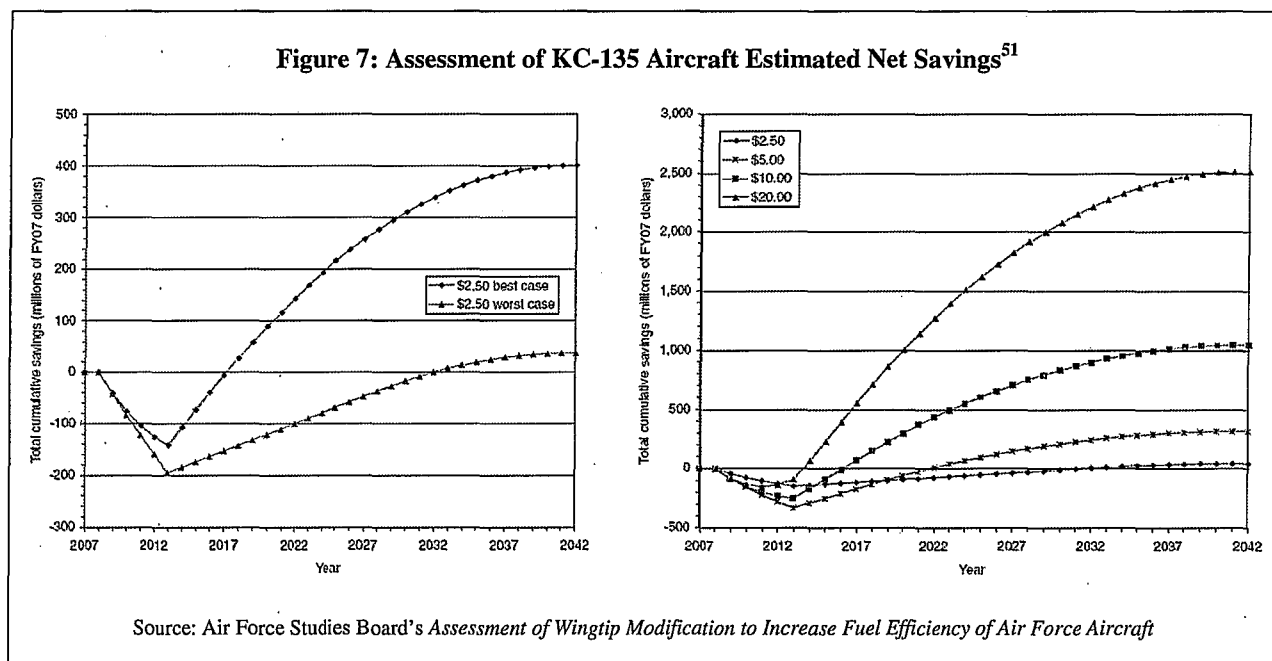
By 1981, the Air Force and NASA completed all research on the KC-135 winglet program; and held a review of the results at the Dryden Flight Research Center on 16 September 1981, publishing their conclusions on the positive impact of KC-135 winglets in *KC-135 Winglet Program Review*.⁴⁷ Unfortunately for the DoD, the Air Force and NASA concluded their research as fuel prices began to plunge, burying the research and its perceived relevance (see Figure 1). Fortunately for the Air Force, as fuel prices have recently escalated again,

organizations are digging up this previous winglet technology research; and touting the benefits and possibilities of winglets. For example, the Air Force Studies Board (AFSB) published *Assessment of Wingtip Modifications to Increase the Fuel Efficiency of Air Force Aircraft* in 2007, recommending, "The committee's analysis for a broad range of fuel prices and with the data available to it on potential improvements in block fuel savings, modification cost estimates, operational parameters for the aircraft, and so forth indicates that wingtip modifications offer significant potential for improved fuel economy in certain Air Force aircraft, particularly the KC-135R/T and the KC-10."⁴⁸

The AFSB also performed a preliminary net present value analysis on the costs associated with modifying the KC-135 versus the expected fuel savings. The AFSB presented a best and worst case scenario.⁴⁹ In the best case scenario, the AFSB concluded the Air Force would be able to modify all 417 KC-135 aircraft and the net savings would become positive 9 years after starting the modification program. When including expected airframe retirements and replacements, the Air Force would save approximately \$400 million (2007 dollars). In the worst case scenario, the AFSB concluded the Air Force would only be able to modify 217 of the 417 aircraft due to aircraft being retired from the inventory prior to reaching the end of the payback period. Regardless, the net savings would become positive after 24 years and would reach \$36 million (2007 dollars). Therefore, the AFSB saw wingtip modification as a win-win situation.

With the clairvoyance of twenty-twenty hindsight, the AFSB's data has proven overly optimistic when concerning fuel prices. For example, the AFSB calculated its figures based on current fuel prices during 2007 (\$2.50 per gallon). A similar calculation today would require using a fuel cost of approximately \$3.75 a gallon. Although the AFSB's calculations were optimistic and the Department of Energy's *Annual Energy Outlook 2007* predicted fuel price

decreases, the AFSB did address the possibility of rising fuel prices, providing charts for \$5.00, \$10.00, and \$20.00 a gallon and explaining how doubling fuel prices would cut the break even point in half.⁵⁰ This additional data has become a necessary evil with fuel prices' climbing approximately 50 percent over the past year. When using \$3.75 a gallon and interpolating the AFSB's charts, the results paint an even rosier picture for wingtip modification. The new results present a worst case scenario with an 18 year break even point and a net savings of between \$150 and \$200 million—a tremendous improvement over 24 years and \$36 million (see Figure 7). More incredibly, the new results also present a best case scenario with a 7 year break even point and a significant increase in net savings exceeding well over a half a billion dollars.



In using the KC-135 as a case study, it is easy to see the complexities associated with adding winglets to the existing airframe; but it is also impossible to deny the potential savings. Since NASA and the Air Force proved winglets decrease drag with the KC-135, it is no longer a question of whether the technology will save money; it has become a question of if the KC-135's life cycle has enough time remaining to break even on the investment. Unfortunately, every year

debating the issue decreases the chances for a positive net value prior to airframe retirement. Additionally, time appears to increase the relative costs of modification, increasing the break even point from three years in 1977 to approximately 9 years in 2007. Just imagine the billions of dollars which could have been saved had the Air Force begun modifying KC-135's in 1981.

Conclusion and Recommendations

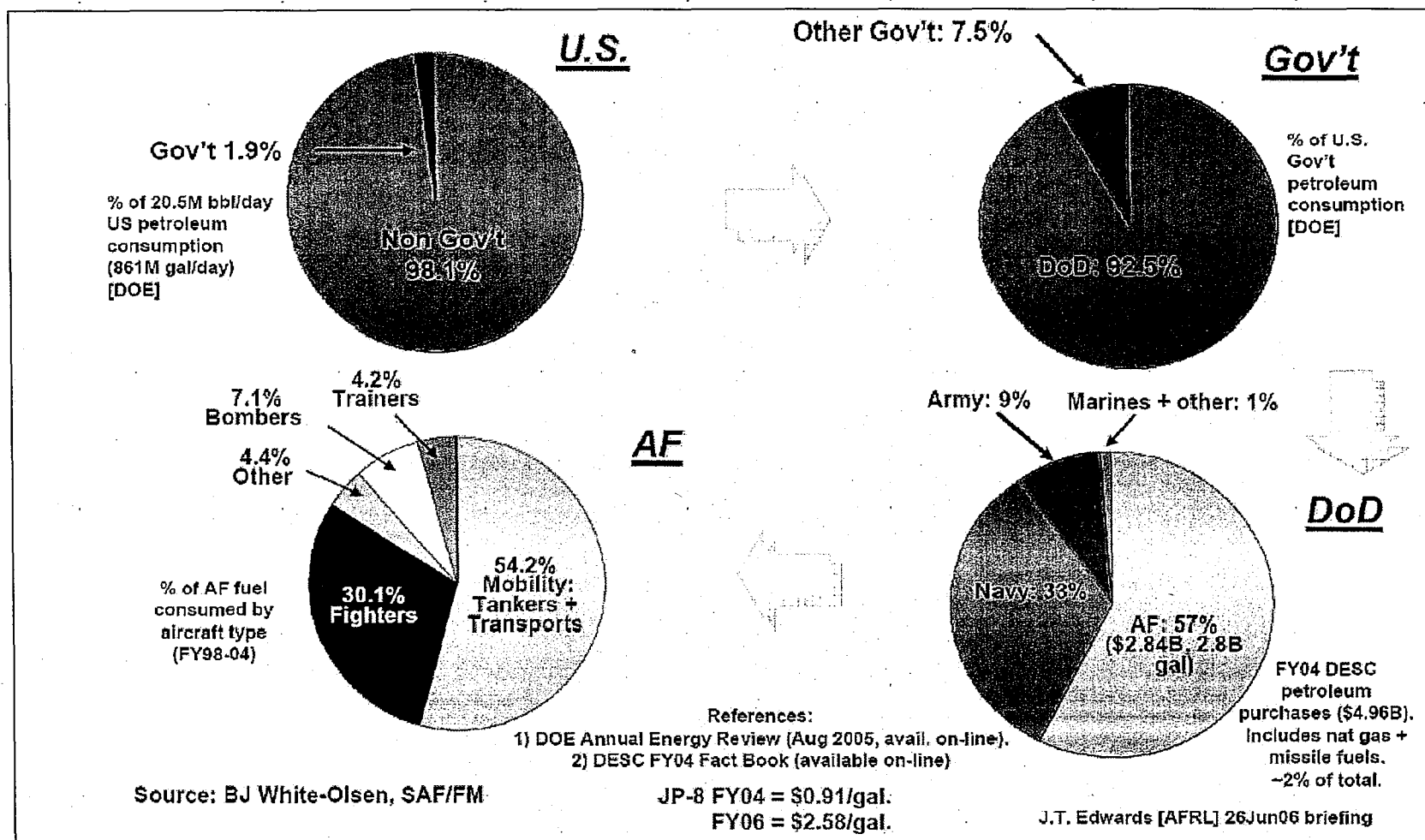
Although the case study focused on the benefits of adding winglets to the KC-135, winglets' ability to decrease fuel consumption is not limited to the KC-135. In addition to the studies on the KC-135, McDonnell-Douglas did parallel studies during the 1970's and 1980's on the DC-10 (the civilian equivalent to the military's KC-10). In their research, McDonnell-Douglas discovered similar benefits to retrofitting the DC-10, finding winglets provided approximately 3 percent fuel savings.⁵² Building on the foundation acquired in its DC-10 studies and grasping the benefits of winglets, McDonnell-Douglas included the winglet concept in its design for the MD-11, the DC-10's successor.⁵³ Additionally, almost all of the aforementioned government reports which cite the advantages of adding winglets to the KC-135 also underscore the benefits of adding winglets to the KC-10. Although no official tests have been done with the C-5 and there is no civilian equivalent to the C-5, seeing how winglets have provided advantages to other jumbo aircraft such as the Boeing 747 leads researchers to believe the same is possible for the C-5. Therefore, the potential exists for gaining benefits from retrofitting all three aircraft platforms throughout the Air Force's mobility fleet.

Two primary issues stand in the way of retrofitting the mobility fleet with winglets, future oil prices and funding. Since the Department of Energy's *Energy Outlook 2008* predicts decreases in oil prices (as did the 2006 and 2007 Energy Outlooks), most key decision makers will follow the path of those in the early 1980's, relying on a strategy of hope.⁵⁴ While most waste time hoping to decrease operating costs via decreases in fuel prices instead of investing in improving aerodynamic fuel efficiencies, history will continue to demonstrate how delaying winglet retrofits is a costly strategy—imagine the billions of dollars and gallons wasted over the past twenty-five years. Eventually, and possibly within the near future, too much time will have

expired; and the aircrafts' life cycles will not have enough time remaining to make retrofitting winglets financially beneficial. Therefore, it is paramount the government waits no longer. The U.S. government needs to learn hope is not a strategy, and needs to make winglets an acquisition priority.

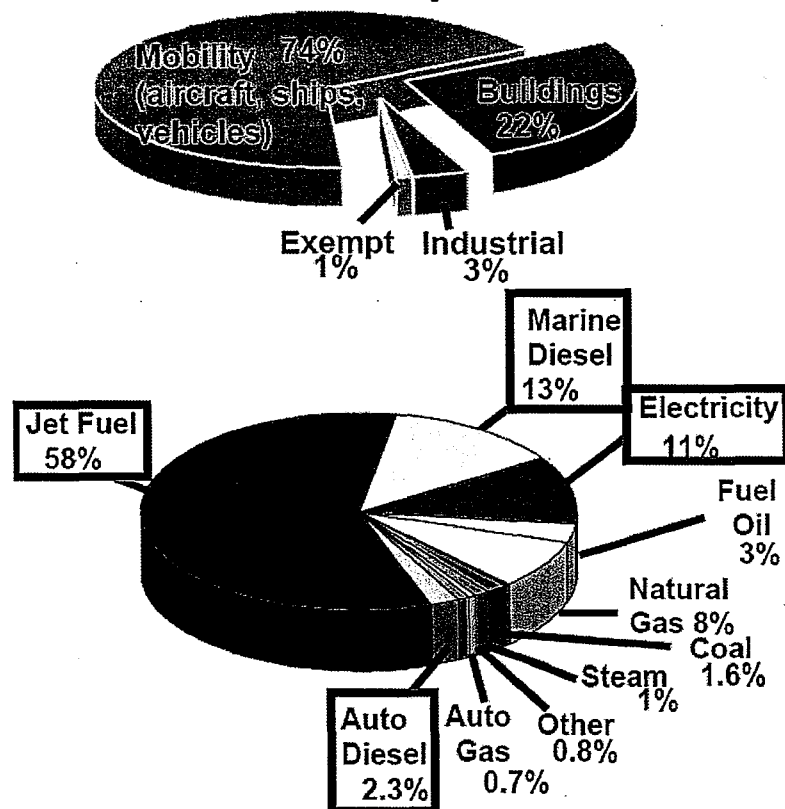
Funding is a more serious roadblock. No one knows the exact price for modifying aircraft with winglets. Using comparable modifications to similar aircraft, researchers estimate the KC-135's modification price to range from \$750,000 to \$1,000,000 per aircraft and the KC-10's modification price to stand at \$1,500,000 per aircraft—unfortunately, with the C-5's situation being so unique, there is no standing estimate for its modification.⁵⁵ Therefore, the initial investment for modifications could have a sticker shock exceeding a billion dollars. The sticker shock alone will sadly keep most key decision makers from being able to support funding the project, regardless of its proven benefits. Therefore, key decision makers need to look beyond the upfront costs; and understand funding winglets as an investment and not as a cost. Only with this shift in mindset will government begin to learn you have to spend money to save money.

Attachment A: U.S. Government, DoD, and U.S. Air Force Fuel Utilization⁵⁶

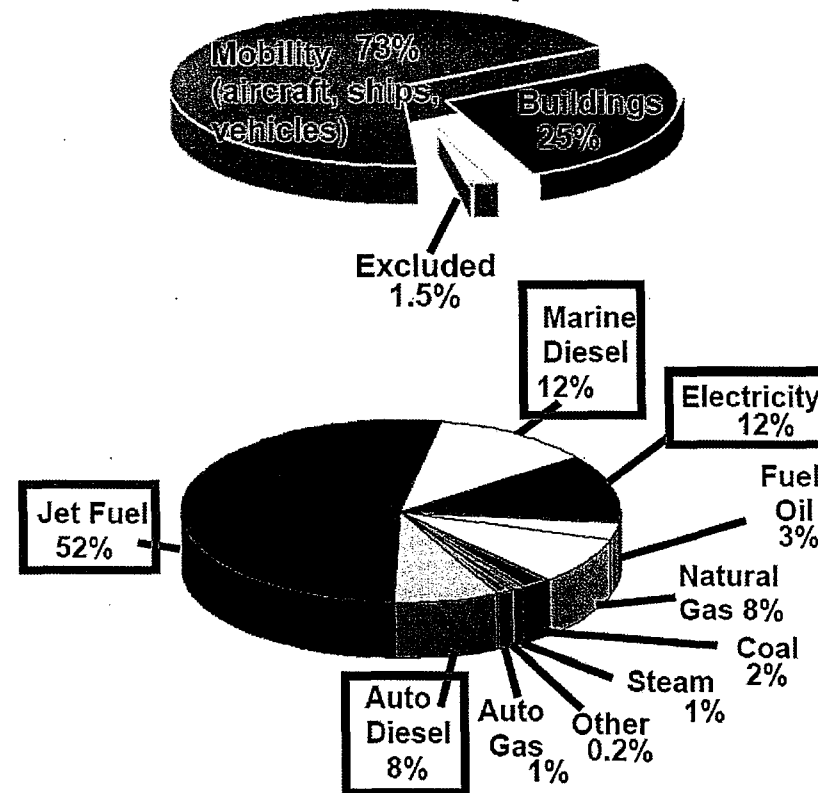


Attachment B: DoD Energy Consumption (FY05 Compared to FY06)⁵⁷

FY05 Consumption

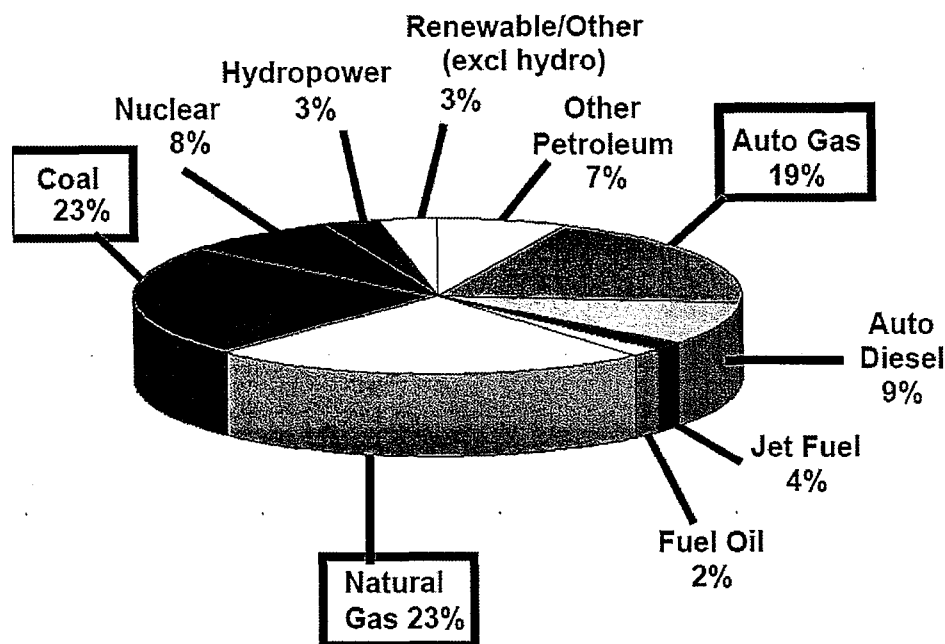


FY06 Consumption



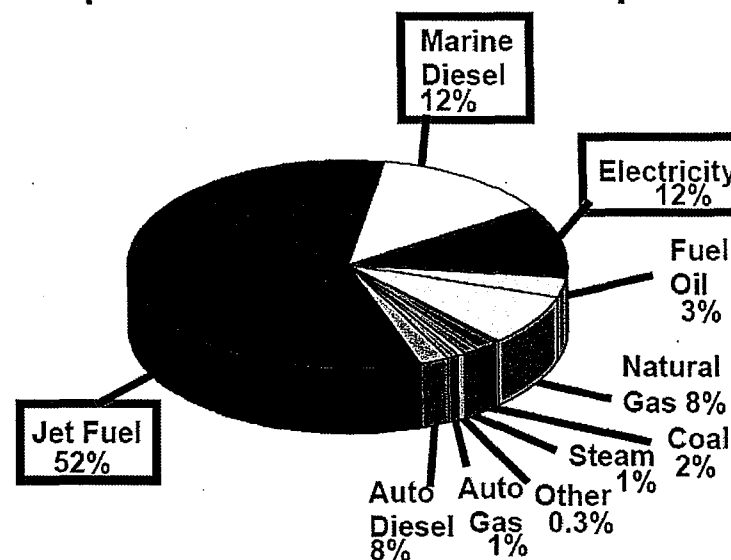
Attachment C: Energy Consumption (DoD Compared to Rest of U.S.)⁵⁸

US Energy Consumption by Type



Source: Energy Information Administration 2005 Consumption Data

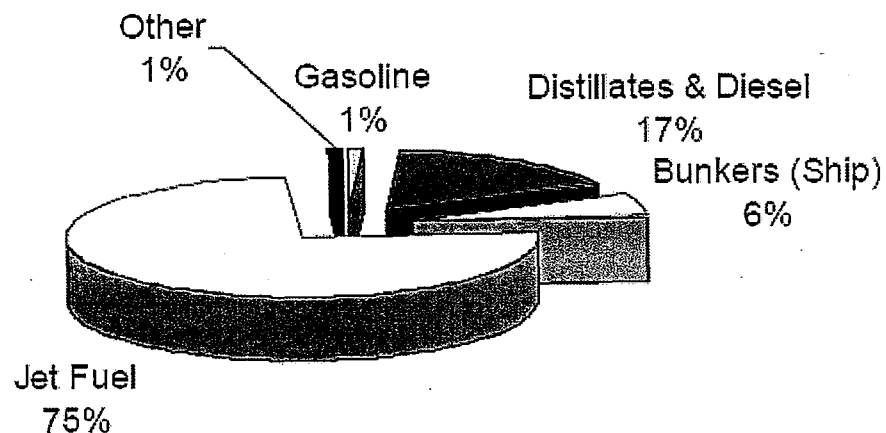
DoD Energy Consumption by Type Represents 1.2% of US consumption



Source: DoD Annual Energy Report for Fiscal Year 2006

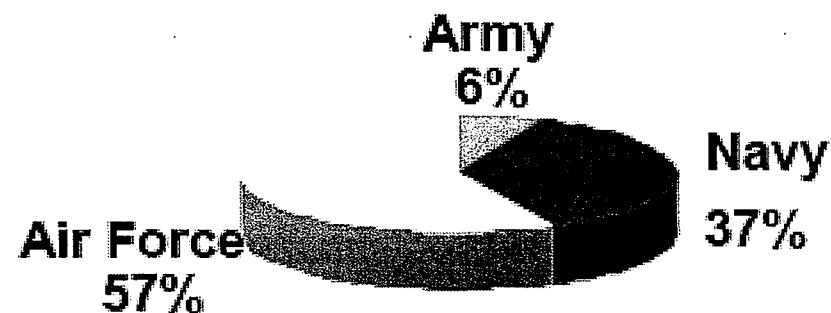
Attachment D: DoD Mobility Use (FY03 – FY05)⁵⁹

Broken Down by Source



Source: Defense Energy Support Center Fact Book, 2005

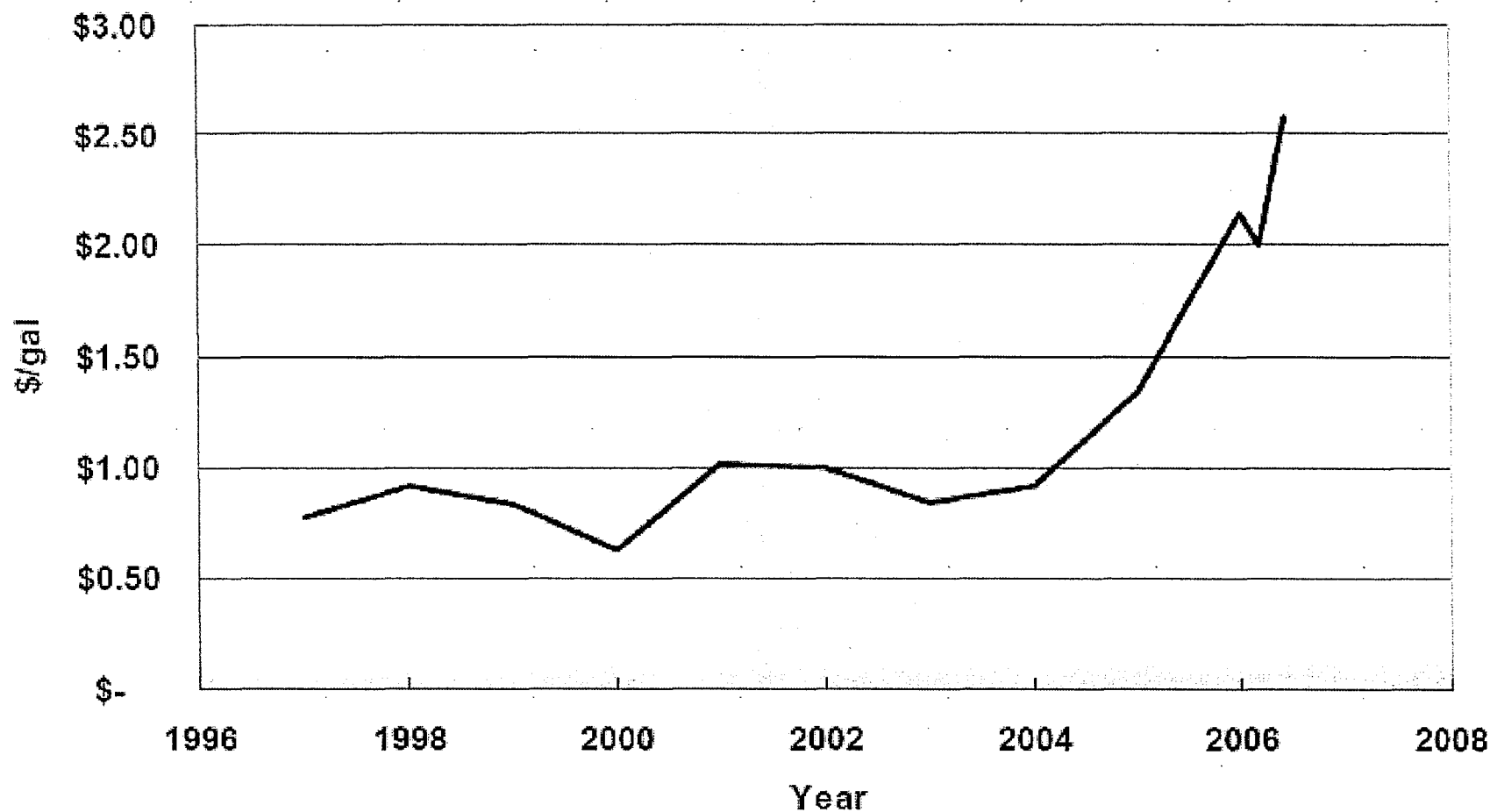
Broken Down by Service



Source: LMI Government Consulting

NOTE: Mobility energy consists almost entirely of petroleum-based products, accounting for 94 percent of DoD's petroleum consumption.

Attachment E: JP-8 (jet fuel) Costs, 1997 to 2007



NOTE: The 280 percent cost increase since 2004 has correlated to over \$4 billion in additional cost for USAF annual fuel expenses.

Source: JASON Report – *Reducing DoD Fossil Fuel Dependence* (JSR 06-135)

End Notes

- ¹ K. K. Ishimitsu et al., *Design and Analysis of Winglets for Military Aircraft* (Seattle: Boeing Commercial Airplane Company, 1976), p 1.
- ² George Santayama, *The Life of Reason* (New York: Dodo Press, 1905), p 284.
- ³ *Petroleum Marketing Monthly* (Washington D.C.: Energy Information Administration, 2008) p 5.
- ⁴ Thomas D. Crowley, Tanya D. Corrie, and David B. Diamond, *Transforming the Way DoD Looks at Energy: An Approach to Establishing an Energy Strategy* FT602T1 (McLean: LMI Government Consulting, April 2007), p 2-7.
- ⁵ "What's with Winglets?" *Aircraft Technology Engineering and Maintenance*, 2007, p 36
- ⁶ Peggy Overbey, "Winglets," Concept to Reality, 17 October 2003, <<http://oea.larc.nasa.gov/PAIS/Concept2Reality/winglets.html>> (accessed December 30, 2007).
- ⁷ U.S. Department of Defense. *Technology Options for Improved Air Vehicle Fuel Efficiencies* SAB-TR-06-04 (Washington D.C.: United States Air Force Scientific Advisory Board, 2006) p 1.
- ⁸ Marc V. Schanz, "Fuel War." *Air Force Magazine*, June 2007, p 46-48.
- ⁹ U.S. Department of Energy. *Annual Energy Review 2006* DOE/EIA-0384 (Washington D.C.: Energy Information Administration 2006), p 24.
- ¹⁰ *Ibid*, p 26.
- ¹¹ Paul Dimotakis, Nathan Lewis, and Robert Grober, *Reducing DoD Fossil-Fuel Dependence* JSR-06-135 (McLean: JASON, The MITRE Corporation, 2006), p 15
- ¹² Thomas D. Crowley, Tanya D. Corrie, and David B. Diamond, *Transforming the Way DoD Looks at Energy: An Approach to Establishing an Energy Strategy* FT602T1 (McLean: LMI Government Consulting, April 2007), p 2-5
- ¹³ Micheal Aimone, Assistant Deputy Chief of Staff/Logistics, Installations and Mission Support, witness statement before the Senate Committee on Finance, 27 February 2007.
- ¹⁴ Paul Dimotakis, Nathan Lewis, and Robert Grober, *Reducing DoD Fossil-Fuel Dependence* JSR-06-135 (McLean: JASON, The MITRE Corporation, 2006), p 15
- ¹⁵ Schanz, Marc V. "Fuel War." *Air Force Magazine*, June 2007, p 46-48.
- ¹⁶ U.S Department of Energy. *Annual Report to Congress on Federal Government Energy Management and Conservation Programs Fiscal Year 2005* (Washington D.C.: Office of the Assistant Secretary, Energy Efficiency and Renewable Energy, 2006), p E-1.
- ¹⁷ Paul Dimotakis, Nathan Lewis, and Robert Grober, *Reducing DoD Fossil-Fuel Dependence* JSR-06-135 (McLean: JASON, The MITRE Corporation, 2006), p 15
- ¹⁸ Michael W. Wynne, U.S. Secretary of the Air Force, *Letter to Airmen: Energy Conservation*, formal letter, 6 September 2006.
- ¹⁹ Breanne Wagner, "Air Force Energy-Saving Plans Face Technical, Financial Hurdles," *National Defense Magazine*, May 2007 <<http://www.nationaldefensemagazine.org/issues/2007/May/AirForceenergy.htm>> (accessed on 15 January 2008).
- ²⁰ Kristine E. Blackwell, *The Department of Defense: Reducing Its Reliance on Fossil-Based Aviation Fuel—Issues for Congress*. CRS Report for Congress RL34062 (Washington D.C.: Congressional Research Service, June 15, 2007), p 2
- ²¹ Major General Frank Faykes, U.S. Air Force, "FY07 Air Force Budget," <<http://www.saffm.hq.af.mil/shared/media/document/AFD-070214-107.pdf>> Power Point slides 22 and 27.
- ²² U.S. Dept of Defense. *More Capable Warfighting Through Reduced Fuel Burden* SuDoc D

1.107:2002019136 (Washington D.C.: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, 2001), p 65-72.

²³ U.S. Department of Defense. *Technology Options for Improved Air Vehicle Fuel Efficiencies* SAB-TR-06-04 (Washington D.C.: United States Air Force Scientific Advisory Board, 2006), p 2

²⁴ Dimotakis, Paul; Lewis, Nathan and Grober, Robert. *Reducing DoD Fossil-Fuel Dependence* JSR-06-135 (McLean: JASON, The MITRE Corporation, 2006), p ?

²⁵ Shaffer, Al. "DoD Energy Security Task Force," 22 May 2007, Power Point slides (accessed 30 December 2007), slide 15.

²⁶ Thomas D. Crowley, Tanya D. Corrie, and David B. Diamond, *Transforming the Way DoD Looks at Energy: An Approach to Establishing an Energy Strategy* FT602T1 (McLean: LMI Government Consulting, April 2007), p E-17.

²⁷ Blackwell, Kristine E. *The Department of Defense: Reducing Its Reliance on Fossil-Based Aviation Fuel—Issues for Congress*. CRS Report for Congress RL34062 (Washington D.C.: Congressional Research Service, June 15, 2007), p 23.

²⁸ *Ibid*, p 29-30.

²⁹ Thomas D. Crowley, Tanya D. Corrie, and David B. Diamond, *Transforming the Way DoD Looks at Energy: An Approach to Establishing an Energy Strategy* FT602T1 (McLean: LMI Government Consulting, April 2007), p C-3.

³⁰ Kristine E. Blackwell, *The Department of Defense: Reducing Its Reliance on Fossil-Based Aviation Fuel—Issues for Congress*. CRS Report for Congress RL34062 (Washington D.C.: Congressional Research Service, June 15, 2007), Summary.

³¹ *Ibid*, p 1.

³² Micheal Aimone, Assistant Deputy Chief of Staff/Logistics, Installations and Mission Support, witness statement before the Senate Committee on Finance, 27 February 2007.

³³ *Assessment of Wingtip Modifications to Increase the Fuel Efficiency of Air Force Aircraft* (Washington, D.C.: National Academies Press, 2007), p x.

³⁴ U.S. Dept of Defense. *More Capable Warfighting Through Reduced Fuel Burden* SuDoc D 1.107:2002019136 (Washington D.C.: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, 2001), p ES-1

³⁵ *Assessment of Wingtip Modifications to Increase the Fuel Efficiency of Air Force Aircraft* (Washington, D.C.: National Academies Press, 2007), p 57.

³⁶ U.S. Dept of Defense. *More Capable Warfighting Through Reduced Fuel Burden* SuDoc D 1.107:2002019136 (Washington D.C.: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, 2001), p ES-2

³⁷ Marty Curry, "National Aeronautics and Space Administration," Winglets, 27 October 2007, <<http://www.nasa.gov/centers/dryden/about/Organizations/Technology/Facts/TF-2004-15-DFRC.html>> (accessed December 30, 2007).

³⁸ The experiments discussed were

Richard T. Whitcomb, *A Design Approach and Selected Wind-Tunnel Results at High Subsonic Speeds for Wing-Tip Mounted Winglets* NASA TN D-8260 (Washington D.C.: National Aeronautics and Space Administration, 1976).

and

Lawrence C. Monoya, Peter F. Jacobs, and Stuart G. Flechner, *Effect of Winglets on a First Generation Jet Transport Wing. III – Pressure and Spanwise Load Distributions*

for a Semispan Model at Mach 0.30 NASA TN D-8478 (Washington D.C.: National Aeronautics and Space Administration, 1977).

³⁹ George W. Loptier, *The Effect of Winglets on the KC-135A Aircraft* Technical Report APFDL-TR-78-124 (Seattle: Boeing Commercial Airplane Company, 1978), p 1.

⁴⁰ *Ibid*, p 1.

⁴¹ Peggy Overbey, "Winglets," Concept to Reality, 17 October 2003, <<http://oea.larc.nasa.gov/PAIS/Concept2Reality/winglets.html>> (accessed December 30, 2007).

⁴² *KC-135 Winglet Program Review* NASA Conference Publication 2211 (Edwards Air Force Base: NASA Dryden Flight Research Center, 1981) p 108.

⁴³ *Ibid*, p 128.

⁴⁴ *Ibid*, p 21.

⁴⁵ *Ibid*, p 145.

⁴⁶ *Ibid*, p 153.

⁴⁷ *Ibid*, p iii.

⁴⁸ *Assessment of Wingtip Modifications to Increase the Fuel Efficiency of Air Force Aircraft* (Washington, D.C.: National Academies Press, 2007), p 3 and 68.

⁴⁹ *Ibid*, p 9.

⁵⁰ U.S. Department of Energy, *Annual Energy Outlook 2007* DOE/EIA-0484 (Washington D.C.: Energy Information Administration, 2007), p 4.

⁵¹ *Assessment of Wingtip Modifications to Increase the Fuel Efficiency of Air Force Aircraft* (Washington, D.C.: National Academies Press, 2007), p 67 and 69.

⁵² A. B. Taylor, *DC-10 Winglet Flight Evaluation Summary Report* NASA Contract Report 3748, (Long Beach: McDonnell-Douglas Corporation, 1983), p v.

⁵³ Peggy Overbey, "Winglets," Concept to Reality, 17 October 2003, <<http://oea.larc.nasa.gov/PAIS/Concept2Reality/winglets.html>> (accessed December 30, 2007).

⁵⁴ U.S. Department of Energy, *Annual Energy Outlook 2008* DOE/EIA-0383 (Washington D.C.: Energy Information Administration, 2007), p 3.

⁵⁵ AFSB Report.

⁵⁶ Paul Dimotakis, Nathan Lewis, and Robert Grober, *Reducing DoD Fossil-Fuel Dependence* JSR-06-135 (McLean: JASON, The MITRE Corporation, 2006), p 14.

⁵⁷ Al Shaffer, "DoD Energy Security Task Force," 22 May 2007. Power Point slides (accessed 30 December 2007), slide 10.

⁵⁸ *Ibid*, slide 11.

⁵⁹ Thomas D. Crowley, Tanya D. Corrie, and David B. Diamond, *Transforming the Way DoD Looks at Energy: An Approach to Establishing an Energy Strategy* FT602T1 (McLean: LMI Government Consulting, April 2007), p 2-6 and A-1.

Bibliography

- Aimone, Micheal, Assistant Deputy Chief of Staff/Logistics, Installations and Mission Support. Witness statement before the Senate Committee on Finance, 27 February 2007.
- Blackwell, Kristine E. *The Department of Defense: Reducing Its Reliance on Fossil-Based Aviation Fuel—Issues for Congress*. CRS Report for Congress RL34062. Washington D.C.: Congressional Research Service, June 15, 2007.
- Curry, Marty. "National Aeronautics and Space Administration." Winglets. 27 October 2007. <<http://www.nasa.gov/centers/dryden/about/Organizations/Technology/Facts/TF-2004-15-DFRC.html>> (accessed December 30, 2007).
- Crenshaw, Kent R, Captain, USAF. *Stability and Control Characteristics of the Winglet Configured KC-135A*. Wright-Patterson Air Force Base: Air Force Institute of Technology, 1976.
- Crowley, Thomas D., Corrie, Tanya D., and Diamond, David B. *Transforming the Way DoD Looks at Energy: An Approach to Establishing an Energy Strategy* (Report FT602T1). LMI Government Consulting, 2007.
- Defense, U.S. Dept of. *Defense Science Board Task Force Report on Aerial Refueling Requirements*. Washington D.C.: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, 2004
- Defense, U.S. Dept of. *More Capable Warfighting Through Reduced Fuel Burden* (SuDoc D 1.107:2002019136). Washington D.C.: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, 2001
- Defense, U.S. Dept of. *Technology Options for Improved Air Vehicle Fuel Efficiencies* (SAB-TR-06-04). Washington D.C.: United States Air Force Scientific Advisory Board, 2006.
- Dimotakis, Paul; Lewis, Nathan and Grober, Robert. *Reducing DoD Fossil-Fuel Dependence* (JSR-06-135). McLean: JASON, The MITRE Corporation, 2006.
- Energy, U.S. Dept of. *Annual Energy Outlook 2008* (DOE/EIA-0383). Washington D.C.: Energy Information Administration, 2008.
- Energy, U.S. Dept of. *Annual Energy Outlook 2007* (DOE/EIA-0484). Washington D.C.: Energy Information Administration, 2007.
- Energy, U.S. Dept of. *Annual Energy Review 2006* (DOE/EIA-0384). Washington D.C.: Energy Information Administration, 2006.
- Energy, U.S. Dept of. *Annual Report to Congress on Federal Government Energy Management and Conservation Programs Fiscal Year 2005*. Washington D.C.: Office of the Assistant

Secretary, Energy Efficiency and Renewable Energy, 2006.

Energy, U.S. Dept of. *Petroleum Marketing Monthly [January]*. Washington D.C.: Energy Information Administration, 2008

Faykes, Frank, Major General, U.S. Air Force. "FY07 Air Force Budget."
<<http://www.saffm.hq.af.mil/shared/media/document/AFD-070214-107.pdf>> Power Point slides 22 and 27 (accessed December 30, 2007).

Flechner, Stuart G. *Effects of winglets on first-generation jet transport wing (NASA technical paper)*. Oaklahoma City: The National Technical Information Service, 1979.

Ishimitsu, K. K., VanDevender N., Dodson, R. O., Brault, P. C., and Byers, B. A. *Design and Analysis of Winglets for Military Aircraft* (Technical Report AFFDL-TR-76-6). Seattle: Boeing Commercial Airplane Company, 1976.

Loptier, George W. *The Effect of Winglets on the KC-135A Aircraft* (Technical Report APFDL-TR-78-124). Seattle: Boeing Commercial Airplane Company, 1978.

Maughmer, Mark. "About Winglets." About Winglets. http://www.xs4all.nl/~arjanvd/winglets_percent20by_percent20Mark_percent20Daughmer.pdf (accessed December 30, 2007).

Montoya, Lawrence C. *KC-135 Winglet Flight Results (DFRC 80-593)*. Edwards Air Force Base: NASA Dryden Flight Research Center, 1980.

Overbey, Peggy. "Winglets." *Concept to Reality*. 17 October 2003.
<<http://oea.larc.nasa.gov/PAIS/Concept2Reality/winglets.html>> (accessed December 30, 2007).

Santayana, George. *The Life of Reason (Part V)*. New York: Dodo Press, 1905.

Schanz, Marc V. "Fuel War." *Air Force Magazine* June 2007: 46-48.

Shaffer, Al. "DoD Energy Security Task Force." 22 May 2007. Power Point slides (accessed 30 December 2007).

Taylor, A. B. *DC-10 Winglet Flight Evaluation Summary Report* (NASA Contract Report 3748). Long Beach: McDonnell-Douglas Corporation, 1983.

Wagner, Breanne. "Air Force Energy-Saving Plans Face Technical, Financial Hurdles" *National Defense Magazine*, May 2007.

Williams, James L. "Oil Price History and Analysis." *WTRG Economics*.
<<http://www.wtrg.com/prices.htm>> (accessed October 31, 2007).

Wynne, Michael W., U.S. Secretary of the Air Force. *Letter to Airmen: Energy Conservation*. Formal letter, 6 September 2006.

Assessment of Wingtip Modifications to Increase the Fuel Efficiency of Air Force Aircraft. Washington, D.C.: National Academies Press, 2007.

Defense Energy Support Center Fact Book, Fiscal Year 2005 (ADA472201). Fort Belvoir: Defense Energy Support Center, 2005.

KC-135 Winglet Program Review (NASA Conference Publication 2211). Edwards Air Force Base: NASA Dryden Flight Research Center, 1981.

"What's with Winglets?" *Aircraft Technology Engineering and Maintenance*. Paris. 2007.